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Investigation on heat transport in hyporheic zone using flume simulation and modeling

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Investigation on heat transport in hyporheic zone using flume simulation and modeling

by

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Report

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For my parents

who nourish me and support me to reach my goal

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Abstract

Investigation on heat transport in hyporheic zone using flume simulation and modeling

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The University of Texas at Austin, 2011

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Recent research has shown that groundwater flow in hyporheic zone is critical in major hydrologic, ecological, and biogeochemical processes. Quantitative analyses from the literature show that there is a strong correlation between the diel cycles in pH, water temperature, and other parameters such as trace metal concentrations. There is, however, no controlled experimental data to illustrate how water temperature influences the trace metal concentrations and other parameters. The research study presented here illustrates the mechanism of heat is transported from stream water to groundwater in the hyporheic zone on different bed form. The work will serve as the foundation of future research in understanding the relationship of heat and trace metal concentrations in the sediments.

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Chapter 1. Introduction

Problem Statement

Human population has been increasing at a stunning rate in the recent decades. It is expected that such rapid growth will growth in the near future (Cohen 2003). Many resources, for instance, food and energy, are required to be available in the same rate to sustain this population growth. Industrial manufacturing and food production are seen to undergo explosive expansion and development to secure our living. These developments, however, is taking place at the expense of the environment (Varis and Vakkilainen 2001). For instance, the use of coal as a nonrenewable energy resource in developed and developing countries, like the United States and China, is driving the expansion of the mining industry. The extraction of coal from mines releases various contaminants into the nearby water body such as rivers. On the other hand, aggressive use of inorganic fertilizers to boost agricultural production contributes to the unnatural levels of nitrates and phosphates in rivers and coastal regions. The discharge of these contaminants into the water body put significant stress on the local ecosystem and biotic species (Nimick *et al*. 2003).

In addition, global warming is an undeniable fact, which is causing an increase in air temperature and water temperature. To focus only on the increasing temperature of water in river, the extra heat energy in the river severely alters the condition of the local ecosystems (Mohseni *et al*. 2003, Caissie 2006). The rising temperature endangers the survival of biotic species because most of them, unlike human, have minimal tolerance in surrounding temperature (Carpenter *et al*. 1992). It, then, leads us into a question: How does the natural system respond to the human-induced stresses? In particular, how does the river setting react with the stresses?

Research Objectives

This research was performed to investigate the heat exchange of groundwater in the hyporheic zone. A hyporheic zone is formed when the groundwater is recharged by the downwelling of stream water and discharged, through upwelling, into the stream over a short distance. It is proven from computer modeling (Cardenas and Wilson 2007b) that the heat exchange method in the hyporheic zone is primarily through advection. The advective heat transport, hence, induces a different flow pattern of fluid in the hyporheic zone. The significance of this finding is that the flow pattern in the hyporheic zone may help explain the diurnal cycles of metallic ions and nutrients due to the sorption processes in the hyporheic sediments. The goal of this research is to validate the findings from computer modeling in empirical setting. The investigation will lay the foundation of future research on understanding the influence of heat exchange on the diurnal cycles of various ions.

This study's specific objectives include:

1. To analyze the heat exchange pattern in the hyporheic, zone; and
2. To analyze the heat exchange pattern in the hyporheic zone at pool-riffle-pool topography.

In the literature published by Gammons *et al.* (2005), it is shown that iron and other heavy metals are exhibiting diurnal fluctuation in the stream water. While the authors suggest a strong correlation between pH and the diurnal cycles observed, in which the change in pH in the stream is due to the photosynthesis and respiration of plants, there is no evidence to support the claim that pH. There is no research study investigating how pH or water temperature affects the diurnal cycles. This study is, therefore, to establish a controlled experiment on how water temperature affects the flow of hyporheic water. Consequently, in the future research, the study between the flow of hyporheic water and water chemistry in the hyporheic zone will be conducted.

Organization of the Report

Chapter 2 of the report will consist of literature review that explains the background of the research. It will, first, discuss the fundamental understanding of groundwater flow, followed by the importance of hyporheic zone. Then, it will summarize the current research findings on the diurnal cycle of heat in hyporheic zone and the biogeochemistry in hyporheic zone. The chapter will end with a review on literature discussing the diurnal cycles of minerals and metallic ions.

Chapter 3 will describe the methods used in this research study, beginning with a comprehensive description of the experimental setup. It will, then, explain the methods, in which the data is collected.

Chapter 4 will present the results from the six experiments conducted. It is followed by a discussion and conclusion on the research study.

Chapter 5 will offer a reflection on the value of the research experience to me as a geoscience student and a science educator. This chapter is divided into four sections:

better understanding on groundwater, visualizing the underground process, developing a vision in geology, and understanding the complexity of geological setting.

Chapter 2. Background

Understanding Groundwater Flow in Hyporheic Zone

Groundwater is the water residing in aquifers below the land surface. It is formed by the percolation of surface water through the sediments or seepage from water bodies such as rivers, lakes, or oceans. Groundwater can be discharged through a well or into any water body. Typical groundwater is considered to have a long residence time in the aquifer because of slow velocity affected by its viscosity and the porosity of the sediments.

In the hyporheic zone, however, the distance of recharge and discharge is relative close and the residence time is very short, compared to typical groundwater. Cozzetto *et al*. (2006) cited an explanation by Poole and Berman (2001) that hyporheic groundwater consists of the of stream water that enters the sediment, travels in the subsurface, and discharges into the stream at a downstream location. The residence time of hyporheic groundwater can be as short as several minutes or weeks.

To determine the velocity of hyporheic groundwater, heat can be used as a tracer of hyporheic flow (Constanz 2008). This is made possible due to the advective heat transport in hyporheic groundwater. Permeability of sediments in the streambed plays a major in determining the velocity of hyporheic flow and the volume of hyporheic zone. Cardenas and Wilson (2006) points out that higher permeability positively correlated to a faster velocity of hyporheic flow and greater volume of the hyporheic zone. The nature of sediments, hence, contributes to the properties of the hyporheic zone.

Importance of Hyporheic Zone: Interactions between Stream Water and Groundwater

In the experiments conducted by Cozzetto *et al*. (2006) at Fryxell Basin, Antarctica, it showed that the advection of warmer stream water is responsible for the erosion of frozen boundary. Such effect is profound during summer time, causing the expansion of hyporheic zone. The authors concluded that interaction between the hyporheic groundwater and stream water influences hydrologic, biogeochemical, and ecological processes in the streams.

Boulton *et al*. (1998) pointed out that the interaction between stream water and groundwater is important to ecological processes. For instance, inorganic nitrogen can be regenerated in hyporheic zone and become available to nutrient-limited surface biota in the downstream. Cardenas and Wilson (2007a) are in agreement with Boulton *et al*. that the exchange between stream water and groundwater affects biogeochemical and ecological process in a variety of aquatic settings. Cardenas and Wilson (2007b) reiterated the importance of hyporheic zone by stating that the discharge of hyporheic groundwater provides thermal refugia for some organisms and affects fish spawning. The detail of the water chemistry will be discussed later in the chapter.

Diurnal Cycle of Heat in Hyporheic Zone

Stream water exhibits diel cycle during a sunny day because the water absorbs the heat energy from the sun by solar radiation. The heat energy in the stream water can be transferred to hyporheic water by conduction or advection or both. According to Cardenas and Wilson (2007a), the thermal influence by conduction is only effective for approximately 25cm underneath the sediment surface. When advection and conduction are both effective, the diel thermal forcing can be effective to 50cm in depth. The heat transportation requires the stream water to enter into the sediments, becoming hyporheic groundwater and carrying the heat energy into the streambed. A field study at Jaramillo Creek, New Mexico, by Swanson and Cardenas (2010) illustrated that shallow hyporheic flow contributes to the pronounced thermal variation across the pool-riffle-pool sequence. The conceptual model in the study suggested that the downwelling of stream water into the sediments is responsible for the advective heat transport into the streambed.

Diurnal Cycles in Hyporheic Zone: Significance in Biogeochemistry

As mentioned earlier, the interaction of stream water and groundwater has a significant impact in the hyporheic zone. A field study at Lot River, France, conducted by Bourg and Bertin (1996) showed that pH, dissolved oxygen, and zinc presented diurnal cycles in the river. The authors claimed that the diurnal cycle of zinc was the result of a pH-dependent geochemical process where the solubility of zinc was controlled by the adsorption and desorption processes of the sediments. The observed dissolved oxygen and pH variations in the river were due to photosynthesis and respiration of aquatic biota. The author believed that the coupling of biological activity and sorption processes correlated to the heavy metal solubility in rivers. A literature published by Huettel *et al*. (1998) indicated that advective transport in the hyporheic zone was important in controlling biogeochemical zonations and fluxes in permeable sediment beds. The topography of the sediments and the advective hyporheic flow jointly contributed to the release of reduced metal species.

Diurnal Cycles of Minerals and Metallic Ions: Temperature or pH driven?

Nimick *et al*. (2003) observed the concentrations of Cd, Mn, Ni, and Zn in 12 neutral to alkaline streams draining historical mining areas in Montana and Idaho. The metal species experienced diel variation between 119% and 500%. The study established a strong correlation between pH and the concentrations of the metal species. The study also suggested pH and water temperature were the possible factors in causing the diurnal cycles of metal species because these parameters were highly correlated.

In a similar study conducted by Gammons *et al*. (2004) at Fisher Creek, Montana, it showed that the concentration of ferrous ion displayed a diel cycle due to acidic pH and photoreduction. It was, however, unable to isolate the effect of acidity on the ferrous ion concentration because water temperature also exhibited diel cycle during the observation. Thus far, there is no quantitative analysis on how much the pH or water temperature contributes to the diel cycles on mineral and trace metal concentrations.

Chapter 3. Methodology, Results, and Discussion

Methodology

We employ the use of a custom-built open-channel flume that allows a maximum flow rate of 550 liters per minute (LPM) and a tilt angle between 0 to 5 degrees. The flume is insulated with household insulation commonly used in attics to minimize heat gain from the ambient environment (Temperature = 26°C). The water temperature is maintained at a preset temperature cycle between 16 to 20 degrees Celsius by a heater to resemble natural diurnal cycle of water temperature. The tilt angle of the flume is set to 1° to assimilate the incline in natural setting. The specification of the sediment used is shown in Table 1.

The temperature is monitored by nineteen Onset® U12-008 4-Channel external data loggers (Figure 1). Eighteen data loggers record the temperature in the sediment bed and one data logger records the stream water temperature. Each logger is attached with a maximum of four working Onset® TMC6-HD water temperature sensors. The sensors for recording groundwater temperature are inserted between 130 cm and 380 cm from the upstream (Figure 2). This is the location where hyporheic zone is likely to form. The loggers are spread at a 20 cm interval except the ones between 230 cm and 280 cm from the upstream, where loggers are separated by only 15 centimeters. The arrangement is made to better illustrate the temperature profile in pool-riffle-pool topographical setting. Each logger records data at a five-minute interval. The data is, then, extracted from the loggers by the accompanied Onset® HOBOware data logging program. The data can be exported to a Microsoft Excel® compatible spreadsheet files for each logger. The temperature data is then compiled to a comma-separate-value (CSV) spreadsheet and used for MATLAB simulation. The resulting product is a temperature field through time animation. Figure 3 shows a snapshot of the animation of experiment 4 at 2945 minutes

Table 1. Specification of Sediment Bed in Flat Bed Setting

Length	Width	Depth	Sediment Type
500 cm	30 cm	72 cm	Gravel

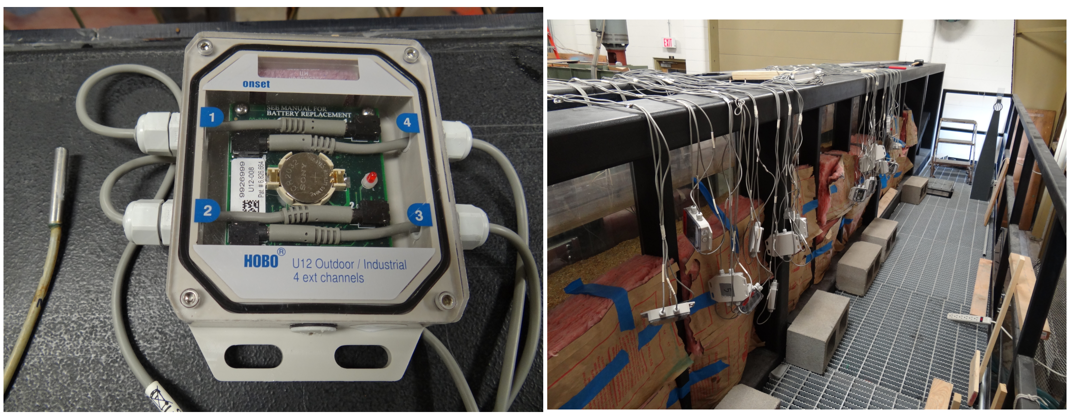

Figure 1. (left) Onset® U12-008 Data Logger with sensor; (right) Location of loggers at the flume

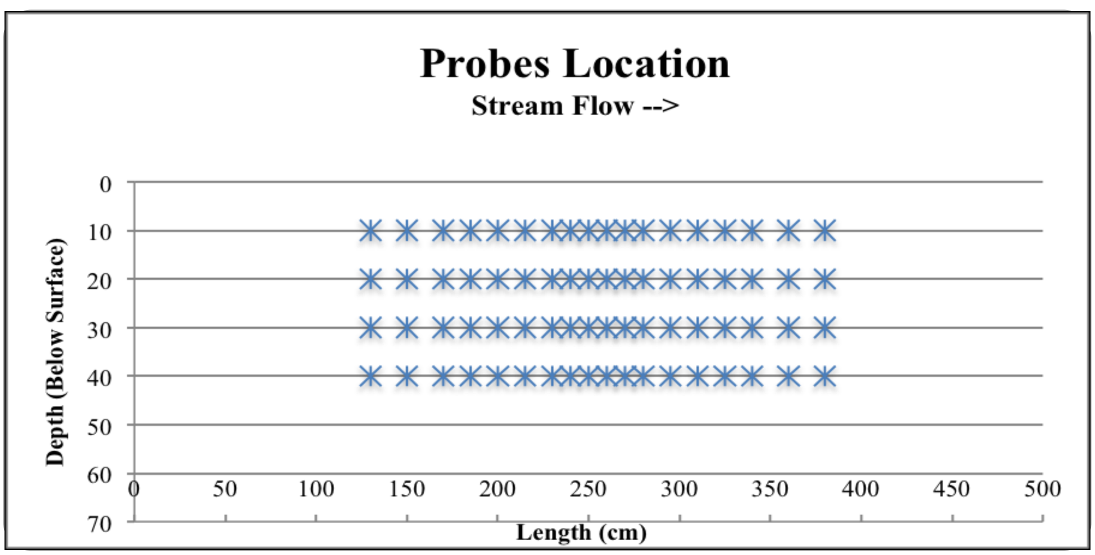

Figure 2. Location of Temperature Probes in the Sediments

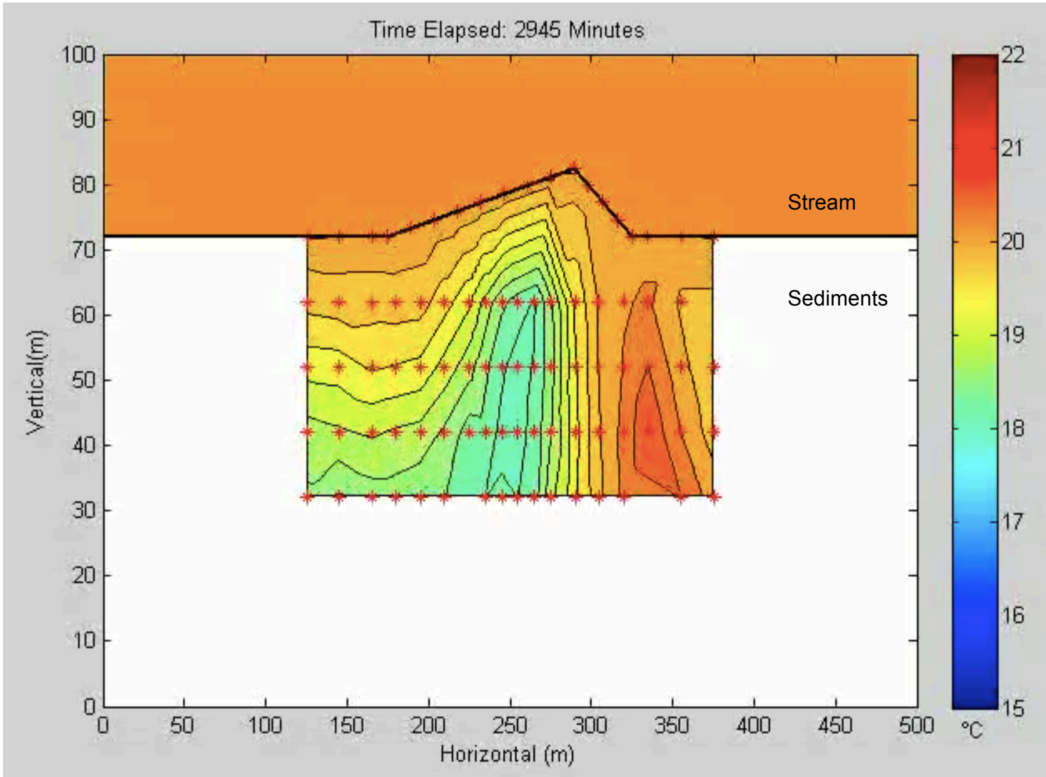

Figure 3. Temperature field through time at 2945 minutes for Experiment 4. The red crosses illustrate the location of the temperature sensors. The stream temperature is represented by the color above the sediment surface.

There are a total of six experiments in this research study, controlling one parameter (flow rate or topography) for each experiment (Table 2). Each experiment is subject to 48 hours and 72 hours for flat bed and pool-riffle-pool topographical setting, respectively. Only the data of the final 24 hours is used in the study. The first 24 or 48 hours of each experiment, depending on the topography, will allow the flume to equilibrate so that accurate experimental data is obtained.

For the pool-riffle-pool topography, the riffle is built at 185 cm from the upstream. The length of the entire riffle is 150 cm and the crest of the riffle is located at the 290 cm from the upstream. The height of the crest is approximate 11 cm. The slope is approximate 6 degrees for the stoss side and 12.5 degrees on the lee side.

Table 2. Experimental Setup for the Designed Experiments

Experiment	Topography	Time (hours)	Flow Rate (LPM)	Tilt Angle	Temperature
1	Flat bed	48	500	1°	16°C to 20°C (24-hour cycle)
2	Flat bed	48	250		
3	Flat bed	48	125		
4	Pool-riffle-pool	72	500		
5	Pool-riffle-pool	72	250		
6	Pool-riffle-pool	72	125		

Results and Discussion

To analyze the heat transport mechanism of hyporheic water, the study employs the use of normalized-temperature amplitude (T*) as discussed in the article published by Cardenas and Wilson (2007b):

$$T^*(x_1, x_2) = \frac{T_{max} - T_{min}}{2T_{amp}} \tag{1}$$

where T_{max} and T_{min} are the maximum and minimum temperature, respectively, at each logger position (x_1, x_2) over a 24-hour period. T_{amp} is the absolute difference between the average temperature and maximum (or minimum) temperature, which, in this research study, is 2°C. A reading of $T^* = 1$ indicates that the hyporheic water at a given location experience the entire temperature range of diel forcing and a T* ~ 0 indicates that the forcing is ineffective.

The normalized-temperature amplitude is plotted on a normalized-temperature amplitude versus length (from stream bed) graph by MATLAB. Figure 4 shows the normalized-temperature amplitude of flat bed at different flow rate (Experiment 1 – 3) while Figure 5 is for pool-riffle-pool topography (Experiment 4 – 6).

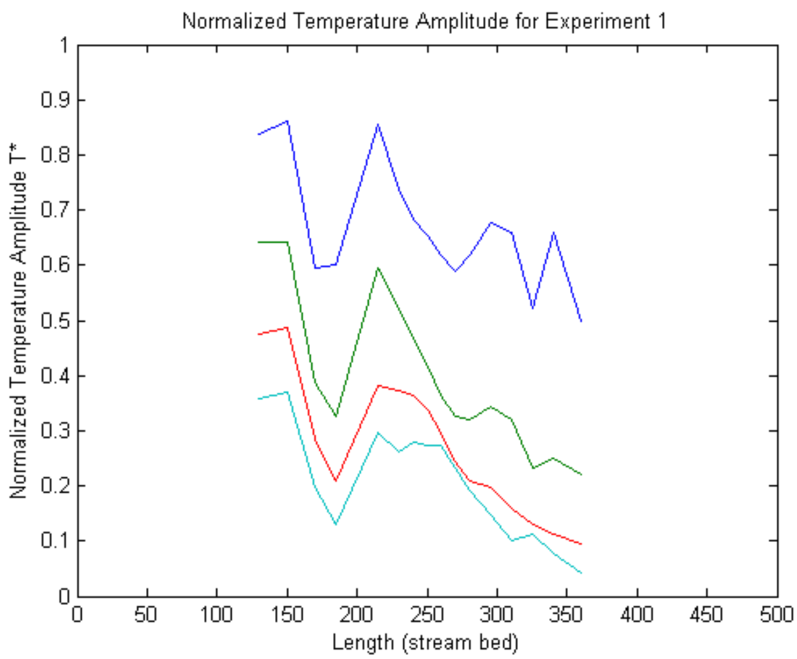

Figure 4 (a)

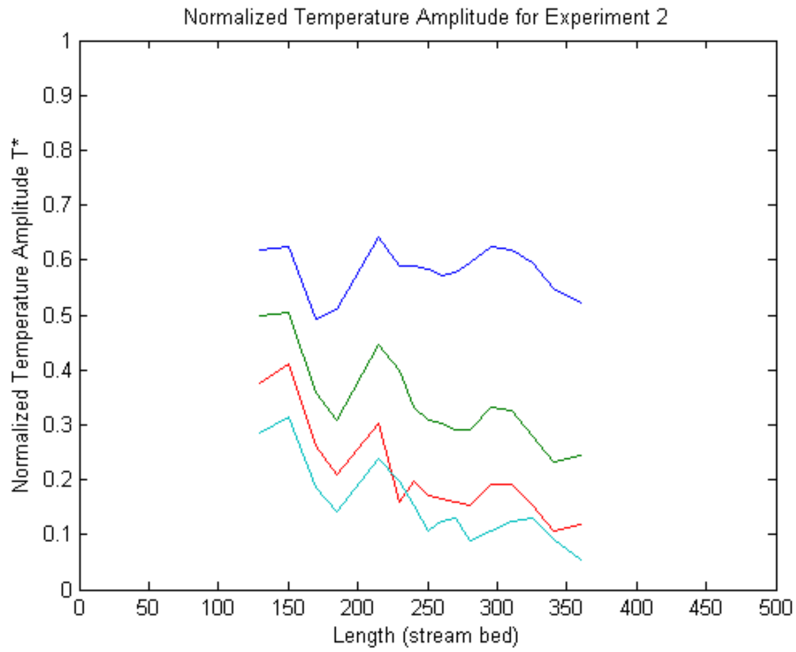

Figure 4 (b)

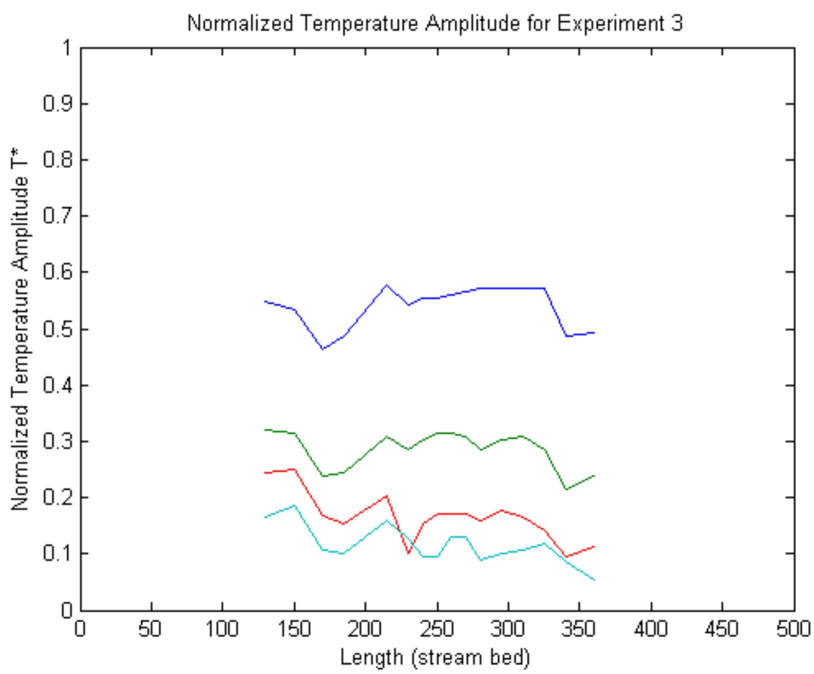

Figure 4 (c)

Figure 4. Normalized-temperature amplitude graphs for Experiment 1 – 3 (a-c). Readings at 10cm depth from the surface are represented by blue-colored line, 20cm depth by green-colored line, 30cm depth by red-colored line, and 40cm by cyan-colored line.

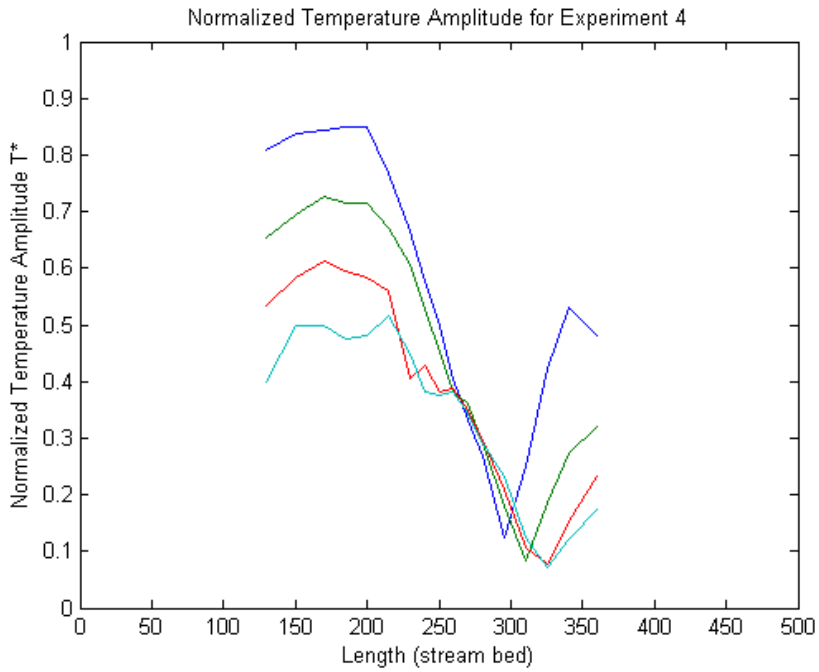

Figure 5 (a)

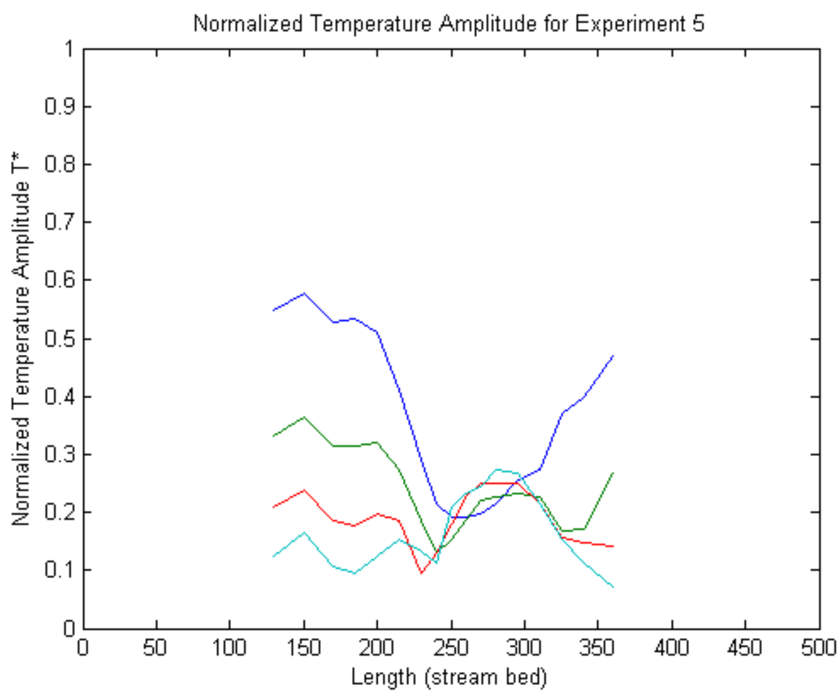

Figure 5 (b)

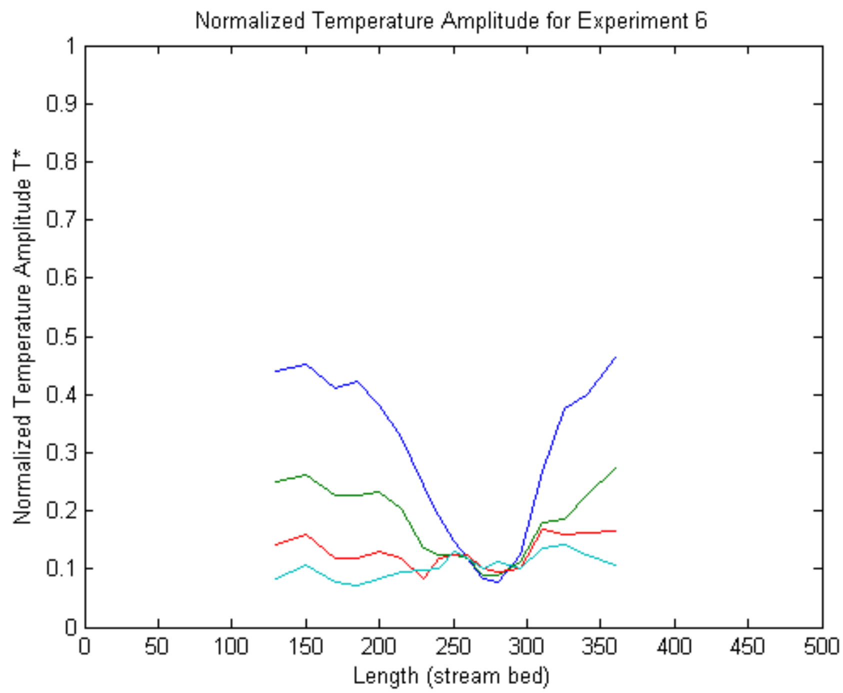

Figure 5 (c)

Figure 5. Normalized-temperature amplitude graphs for Experiment 4 – 6 (a-c). Readings at 10cm depth from the surface are represented by blue-colored line, 20cm depth by green-colored line, 30cm depth by red-colored line, and 40cm by cyan-colored line.

According to Cardenas and Wilson (2007b), it shows that conduction is only effective approximately 25cm from the sediment surface. Figure 4 and 5 illustrate the diel thermal forcing is effective as deep as 40cm below the surface. It indicates that advection is the major heat transport mechanism in hyporheic zone. Heat is transported along the hyporheic flow into the sediments, causing the fluctuation in temperature reading. The influence of advection dissipates as hyporheic water travels deeper into the sediments. Another generalization from Figure 4 and 5 is that advective heat transport becomes less efficient when the flow rate decreases. It suggests that flow rate is a critical factor in determining the influence of advection in the hyporheic zone.

The finding in the research study is in agreement with Cardenas and Wilson's (2007b) modeling. In Figure 5, the trough on each graph coincides with the crest of the riffle, suggesting that advective heat transport is insignificant near the region. Such behavior is due to the upwelling of pore water from the sediments (Cardenas and Wilson 2007b). The strong temperature variation on the stoss side of the riffle illustrates that heat is efficiently transported into the sediments by the downwelling of stream water.

The experimental results in this research study confirm the mathematical modeling by Cardenas and Wilson (2007b). The current research work provides a foundation in exploring significance of diurnal cycles in stream water temperature in the hyporheic zone. The future direction of the research is to further resemble the experimental setting to the natural setting and control the temperature as the independent variable. The goal is to quantitatively analyze the influence of diurnal thermal cycle on the concentration of various polluting ions and nutrients.

Chapter 4. Application to Practice

Better Understanding on Groundwater

Groundwater is a critical component in the water cycle. The nature of groundwater is often difficult to perceive because it is, unlike other components in the water cycle, stored in the subsurface, which we rarely have direct interactions with. It is even harder to visualize the recharge and discharge of groundwater without advanced laboratory aids. The understanding of groundwater is essential to everyone because groundwater is a major source of drinking water especially to the regions where drinkable surface water is not readily accessible.

The entire research experience benefits me in terms of the deeper understanding on groundwater. Groundwater is no longer simply a fluid that is stored and flowing underground. The groundwater can serve as a vehicle that helps transport different entities into and out of the subsurface. Such transportation has a major impact to the local ecology, as discussed in the literature. (Bourg and Bertin 1996) The research experience provides me an opportunity to visualize the actual groundwater flowing process, in addition to the description in textbook, and the subtle interactions with the sediments and with stream water in a river setting. While the experience is primarily available to college and graduate students, I can now share it with my fellow students, through images and videos, on how we develop our knowledge on groundwater.

Visualizing the Underground Process

One of the major aspects of hydrology is the understanding the role of groundwater in natural setting. As mentioned in the previous paragraphs, it is difficult for general public to recognize the existence and function of groundwater. It is critical for them to understand the fact that scientists used to feel the same before any instruments were developed. In the research project, our goal is to understand how heat is transported within the sediments. In the process of designing the experiments, proper instruments are required for us to achieve our goal. We may conduct experiments at the field in the natural setting. It will be, however, difficult for us to control the parameters and observe the influence due to the change of one single parameter. The flume used in the experiment is custom-built to fulfill the requirement. It resembles the natural stream setting and the associated heater allows us to control the temperature while other parameters are kept constant. This illustrates the use of scientific method in solving technical problems.

There is a huge contrast between the research experience and what students experience in secondary education because students are often fed with instruments and procedures to perform experiments. The idea of scientific method and inquiry are not fully expressed to the students in the classrooms. The research experience emphasizes the fact that instruments, sometimes, have to be built for us to gain better understanding. The custom-built flume, temperature probes being inserted in the sediments, and computer simulations help us to visualize the novel heat transport mechanism occurring in the sediment at different topographical settings. The experience is valuable to show my students on what it takes to perform a true scientific experiment and deepen our existing understanding.

Development of a Vision in Geology

I am an educator with a chemistry background. I have been a chemistry teacher for three years. When I teach chemistry to my students, it is not just the knowledge that I try to transfer from my mind and textbook to my students. I try to assist my students to acquire the vision that I have toward the surroundings. Let me illustrate the vision with a few examples. If there is a water droplet on a leaf's surface, it is not just a fluid sitting peacefully on the surface. I can *visualize* the water molecules traveling within the droplet and attracting each other to form a spherical surface. I can also *visualize* the water molecules unnoticeably escaping from the water droplet in the process of evaporation and the leaf absorbing the water for its growth. No doubt, for this vision to shape, it requires vast knowledge in the subject domain in an individual mind.

In the previous year, I began teaching environmental science, a subject that is relatively new in teaching experience. I could easily repeat the words from the textbook and teach a lesson. The students, however, were not seeing the environment like a geologist or a geology student. The missing ingredient was the acquaintance of a geology vision. In this research experience, for instance, using dye to trace groundwater helps me to cognitively acknowledge the existence of groundwater flow. It shows me that topographical setting can have a profound influence on groundwater flow. Furthermore, the use of temperature probes helps me to *visualize* the heat, which is invisible to human naked eyes, being transported advectively from the surface into the subsurface. It illustrates the fundamental difference between conduction and advection, two major heat transport mechanisms in groundwater.

We can extend this discussion into the macro-scale of geology. Tectonic plates are moving every second while human beings are living on them. The movement is hardly noticed due to the extremely slow movement. Yet, such movement result in significant changes along the plate boundary, be it the metamorphism of bedrock or the widening of faults. In order to genuinely interest students in geology or any subject, educators should provide means to help students acquire the vision so that objects and processes are not simply superficial facts, but novel consequences of different precursors.

Understanding the Complexity of Geological Setting

To a novice individual, many objects in nature can only be taken superficially. Before involving this research project, the relationship between stream water and streambed sediments was simply a platform, which is the streambed, for the stream water to flow from one point to another. I may be able to acknowledge the possibility of chemical reactions on the sediments based on my previous knowledge in hydrology, but I certainly could not imagine that the variety of chemical reactions are critical in sustaining the local ecological systems. Using the *vision* I mentioned in the last section, when I see a river cutting through a land surface, it will not be merely a fluid traveling on the land surface but a series complicated, subtle processes occurring everywhere in the stream. This transition, I considered, is a *major* pathway to transform a novice into an expert. I

sincerely thank Dr. Cardenas, my supervisor, and Alec, my supervising graduate student, in giving me opportunity to shape myself into a not-so-novice individual.

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Vita

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